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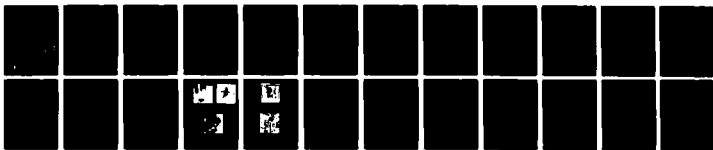
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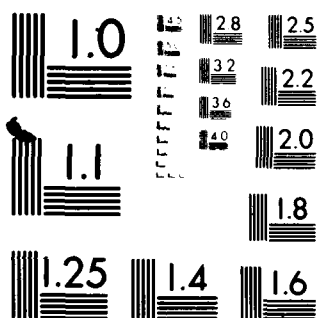
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2 1/2 HOUR DURATION, CLOSED CIRCUIT
LIFE SUPPORT SYSTEM FINAL REPORT
INCLUDING TEST REPORT AND OUTLINE
FOR NIOSH CERTIFICATION

CONTRACT DAAK11-80-C-0059

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2 1/2 HOUR DURATION, CLOSED CIRCUIT LIFE
SUPPORT SYSTEM FINAL REPORT INCLUDING
TEST REPORT AND OUTLINE FOR NIOSH CERTIFICATION

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31 March 1981

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FINAL REPORT, PERIOD 29 MAY 1980 - 31 MARCH 1981

Prepared For: CDR/ARRADCOM
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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER DAAK11-80-C-0049	2. GOVT ACCESSION NO. AD-A099763	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) 2.5 Hour Duration, Closed Circuit Life Support System, Final Report		5. TYPE OF REPORT & PERIOD COVERED Final
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) M.L. Kranz, Project Engineer M.A. Borrello, Design Engineer		8. CONTRACT OR GRANT NUMBER(s) DAAK11-80-C-0059
9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. Divers Co., Survivair Division 3323 West Warner Avenue Santa Ana, California 92702		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS ILC Dover P.O. Box 266 Frederica, Delaware 19946		12. REPORT DATE 4 February 1981
		13. NUMBER OF PAGES 20
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) Chemical Systems Laboratory U.S. AARRADCOM Aberdeen Proving Ground, Maryland 21010		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Breathing Apparatus Life Support Systems Rebreathers		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) A self contained, closed circuit breathing apparatus was developed for ILC Dover for the purpose of life support in a HCPCO (Hazardous Chemical Protective Clothing). Tests were performed to prove the design for life support compatibility over a duration period of 2.5 hours. Peripheral functions of the system were also tested. Recommendations were made from conclusive results. Finally an outline was presented for submitting the system for NIOSH certification.		

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I. PROJECT OBJECTIVE

The project objective was to fabricate a working prototype model of the 2.5 Hour Duration, Closed Circuit Life Support System as described in the development phase of the overall project. The project was to include all items listed in an attachment statement of work on Purchase Order 33402, ILC Dover, Division of ILC Industries, Inc. The ultimate goal, to follow this second phase of the project, is to attain NIOSH approval of the system design.

II. TEST REPORT, 2.5 HOUR, CLOSED CIRCUIT LIFE SUPPORT SYSTEM

A. Objective

Tests, both machine and manned, have been performed on the 2.5 Hour Life Support System to:

1. Determine if the system, by itself, and in conjunction with the HCPCO function according to the intended design in respect to the following parameters:
 - a. Service Life
 - b. Mechanical Operation
 - c. Breathing Gas Concentrations
 - d. Breathing Resistance
 - e. Temperature
 - f. Breathing Bag Permeability - Gasoline
2. Expose, if any, unexpected behavior or unforeseen failure modes of the system.
3. Determine compatibility with human factors such as comfort, fit, etc.

B. Description of Test Apparatus

1. Man Tests: To test the system at a specific design oxygen consumption rate, a treadmill was necessary with instruments for measuring oxygen and carbon dioxide concentrations, temperature and ventilation. Subjects, with recent medical examinations including stress tests, were metabolically measured to determine their specific correlation between treadmill speed and oxygen consumption.

The treadmill used was a Quinton Model No. 18-60 with a Model 644 Programmer. All tests were run at various speeds with a constant 0% grade.

Carbon dioxide and oxygen were monitored by Beckman LB-2 and OM-11 analyzers respectively, which were hooked in series with one another. The sample line ran into a water trap immersed in an ice bath to stop moisture from entering the carbon dioxide test cell. The outlet ran back into the system to complete a closed loop.

The oxygen and CO₂ analyzer output was connected to a linear model 585 strip chart recorder for permanent record.

Temperature, measured at the mouth, was detected with a high response, hypodermic thermocouple connected to a Baily Instrument Model BAT-12 display module. Output from the module was recorded with a six channel, Soltec Model No. KA-61D strip chart recorder.

The recorder also displayed output for ventilation from a Validyne Model CD15 carrier demodulator coupled to a Validyne Model DP45-22 transducer.

For purposes of safety, a Respironics, Exersentry heart rate monitor was used for measuring heart rate.

All measurements were made from the facepiece assembly with the ventilation taken from a fitting in the mask lens and the other connections made through a plastic PVC pipe connection spliced into the inhalation hose, just upstream of the check valve.

2. Machine Tests: Machine tests were performed to measure breathing resistance at a standard respiratory minute volume of 40 lpm. The system interfaced with the test apparatus through a dummy head that allowed a tight seal on the facepiece. Through the mouth of the dummy head, a tube was connected that ran through the back of the head which connected to a breathing machine with a standard 622 Kg-m cam as used by NIOSH. The machine operated with a tidal volume of 1.667 l/breath at a rate of 24 breaths/min. Resistance was measured through a tap that also ran into the vicinity of the mouth and connected on the outside to a Validyne pressure transducer. The signal from the transducer was fed into a Validyne demodulator and the conditioned signal was then recorded on a HP strip chart recorder.
3. Breathing Bag Permeability Test: The permeability test was performed by cycling a breathing bag in an atmosphere saturated with gasoline vapors. The breathing machine was set at 24 breaths/min. with a tidal volume of 1.667 l. The bag was connected to the machine by a hose with an end fitting, simulating the manifold connection. Gasoline concentration was measured at the end of each test with a hand held Draeger pump and sampling tubes for benzene hydrocarbons. See Figure 1 for illustration of test setup.
4. Suit Make-up Regulator Test: The suit make-up regulator test determined the ability of the suit make-up, positive pressure demand regulator to maintain a constant suit pressure, respond to leaks in the suit, and lock-up when suit pressure is achieved.

To test the SMR system, the HCPCO was suspended so as to reduce external pressures from the suit's own weight. The suit make-up demand regulator was removed from the system and connected inside the HCPCO by the quick disconnect, pressure sensing line. See Figure 3. Supply pressure, to the regulator, was supplied through a sealed opening in the HCPCO. Two other connections were made through the wall of the HCPCO; a manometer connection and pressurization line.

C. Basic Procedure

1. Man Tests: After all test instrument connections were made, each test subject was asked to step on the treadmill and was aided in donning the system. The subject then made final adjustments to the system harness to make sure it was secure. Each subject had his own predetermined treadmill speed to simulate an oxygen consumption between 1.4 - 1.7 lpm. The treadmill was then started. See Figures 4 and 5.
2. Suit Make-up Regulator: To test the suit make-up regulator, the suit was completely sealed of leaks after all connections were made. The suit was then inflated through the pressurization line. When the suit achieved an internal pressure of 0.6" water with respect to ambient pressure, the pressurization line was shut off, and the suit make-up regulator was switched on. The regulator was allowed to flow for approximately 10 seconds, then the suit was manually squeezed to activate the regulator diaphragm. The manometer was then read for lock-up pressure.
 - Response to leaking was tested by opening a 1/2" diameter hole in the suit. Pressure was then recorded.

D. Results

Results are discussed according to specific categories and are listed below.

1. Service Life: Man test No. 6 has shown the system duration to exceed the rated duration of 2.5 hours. Breakthrough of any CO₂ was not at all detectable.
2. Carbon Dioxide: Man test No. 3 had shown a consistent, average concentration of 0.04% CO₂ throughout the test. This indicated a small leak past the absorbent bed (see Figure 6). Upon inspection of the canister after the test, it was found that the O-ring was not properly seating against the center conduit which would allow a small portion of exhaled gas to leak through into the inhalation plenum.

All other man tests showed no appreciable levels of CO₂ throughout the testing.

3. Oxygen: Preliminary tests have shown the oxygen level to attain anywhere between 50% - 85% at the initial donning of the system. Over a period of an hour, the oxygen level would rise over 95%, and would soon reach 100%. See Figures 7, 8, 9, and 10. At no time during the man tests did the oxygen level reach unrespirable concentrations. The quantity of oxygen in the cylinder was found to be sufficient for 2.5 hours.
4. Temperature: Preliminary manned tests, without the heat exchanger, have shown the breathing gas temperature to slowly rise over time and level off at a temperature of about 35°C. (See Figure 8).

With the heat exchanger and circulation through the ice reservoir in the HCPCO, breathing temperature was found to vary between 24°C and 27°C for a room temperature of 22°C. (See Figure 10).

5. Resistance: The system breathing resistance was first measured on a breathing machine for a liter volume of 1.667 and a breathing rate of 24 breaths/min. Figure 12 shows the original breathing resistance curve in the facepiece. To reduce the system resistance, each component of the breathing loop was removed and a flow of 120 lpm was passed through the component. This represented the peak flow achieved on the breathing machine. Resistance was tabulated for each component and is shown listed in column A of Table 1 below.

TABLE 1

<u>Component</u>	<u>A</u> <u>Initial Resistance</u>	<u>B</u> <u>Redesign</u>
Canister	1.75	1.00
Hose & Valve	0.45	same
Heat Exchanger	0.95	0.25
Exhalation Plenum	0.35	same
Inhalation Plenum	0.45	same
TOTAL	3.95	2.50
Measured Resistance of Total Systems Peak to Peak	3.20	1.90

Column B describes the change in component and systems resistance after redesign of the heat exchanger and absorbent canister. Resistance was found to decrease by 40%. Figure 3 shows the change in resistance after the redesign.

6. Mechanical Operation: System operations were found to function correctly in every instance, with no apparent complications. System switchover, from PBS to the SBS was found to be smooth with no noticeable discomfort to the user. Automatic switchover is shown in Figure 11. The switchover is noticeable only by a slight increase in breathing resistance. This increase in resistance is due to the setting of the bag exhalation valve which drives the exhalation high. The inhalation cycle in the SBS has a shift, away from zero (positive), due to the limited inhalation through the breathing loop once the inhalation plenum is shut off by the primary breathing loop shutoff valve. (Refer to operation of the system in the maintenance manual for further description.)
7. Permeability of Breathing Bag: Two tests were performed on the breathing bags. The first test lasted for a duration of 5 hours. The concentration of hydrocarbons at the end of this period showed less than 2500 ppm. There were signs of a loose connection that may have caused diffusion of gasoline into the bag.

The test was run again for 2.5 hour duration and the bag was found to contain slightly less than 100 ppm.

E. Conclusions and Recommendations

1. Duration design parameters have been met according to tests. For oxygen consumption at a sedentary rate (0.5 lpm), it was calculated that the duration of the system would be 11.3 hours. For the work rates encountered on the treadmill, the system's oxygen supply should have lasted at least 4 hours. This was not the case. The system was found to last (see Test No. 6, Figure 10) only 2.5 hours. Test No. 6 did have an initial gas loss in donning, but even with the loss taken into account, the system duration should have been longer.

The shorter than calculated duration tends to indicate an external, outward leakage of gas. It is recommended that leaks be located by following the maintenance manual report.
2. Another indication of the system leak is the rising oxygen concentration. Figures 7, 8, 9, and 10 show the rising oxygen level showing a slow replacement by oxygen of nitrogen initially trapped in the system.
3. Resistance in the overall system was reduced by 40% after the redesign of the heat exchanger and canister. Initially the CO₂ absorbent canister measured 8.1" in length and 3.7 in outer diameter with a central conduit of 1-1/8" diameter. The redesign canister was shortened to 6-1/2 inches long with a 4-1/2" diameter inside wall and a 1-1/8" center conduit.

While significantly improving the canister resistance from 1.75 down to 1.00, the change did not however interfere with residence time for CO₂ absorption. There may be a possibility that the bed length could have been reduced even further with an increasing cross sectional area. It is recommended that experimentation be conducted to further optimize the geometry of the canister if time is available.

4. It is recommended that the bag connections be further evaluated for permeability and redesigned if necessary. At its present configuration, it is doubtful if the bags will pass NIOSH.
5. Comfort of the system received critical remarks from most of the test subjects. Recommendations are as follows for improvement of comfort:
 - a. Weight - Weight may be reduced up to six pounds through minor design changes and material selection.
 - b. Harness - The harness should be redesigned so as to distribute more of the weight on the hips, removing a large portion from the shoulders, while at the same time not applying excessive load on the abdomen.
 - c. Facepiece - The center of gravity of the facepiece causes a large moment tending to pull the user's head downward. This tee should be reconfigured to pull the center of gravity in towards the user's head. This tee is pictured on Page 11 of the Operating & Maintenance Instructions.
 - d. Packaging - Packaging at this point has not been optimized for ease of servicing and for external profile.
6. With minor adjustments, the suit make-up regulator was made to operate as designed. Through the testing, it was discovered that absolute lock-up could only be achieved instantaneously if the suit pressure was abruptly increased. Normally the flow would taper off exponentially. To accelerate the lock-up pressure, the suit was mechanically squeezed. This operation could be performed by the user through folding of the arms or bending over.

The suit was found to lock-up at 0.6" - 0.7" H₂O and maintain a positive pressure of 0.2" with a 1/2" diameter, circular leak.
7. Eventually time should be provided for long period system cycling. This would help generate any failure modes that may occur over extended use of the system.

III. FINAL COMMENT

Testing of the 2.5 Hour, Closed Circuit Life Support System has been provided as specified by the contract. It is recommended that further testing be performed, as this test report cannot support any specification as to the degree of reliability for the system. It is, however, the subjective opinions of the authors of this report that if the various engineering changes mentioned are implemented, the design will likely function with high reliability.

Outline of Steps Required for NIOSH Approval

Definitions

A. Quality Control Plan

1. Quality data and control records.
2. Control of engineering drawings and changes.
3. Control of calibration of test equipment.
4. Control of purchased material.
5. Control of lot I.D. processes, manufacturing, fabrication, and assembly.
6. Control of audit, final inspection.
7. Organizational structure to carry out above provisions.

B. Documentation

1. Class A drawings, revised to latest change
2. Specifications showing full details of construction and materials used.
3. Test necessary to compile document parts.

C. Pre-Test Data

1. Test results of same tests to be performed by NIOSH.
2. Report indicating testing compatible with NIOSH testing.
3. Assurance prior to NIOSH submittal that equipment will perform per 30 CFR Part II.

D. Test Required

	30CFR11 Paragraph
1. Bench Tests	
a. Breathing Bag.	11.85-3
b. Breathing Resistance Inhalation.	11.85-5
c. Breathing Resistance Exhalation.	11.85-6
d. Valve Leak Test.	11.85-7
e. Gas Flow	11.85-9
f. Service Time (Man Test 4).	11.85-11
g. CO ₂ Test	11.85-12
h. Low Temperature.	11.85-13
2. <u>Man Test</u>	
a. Test 1: Familiarize wearer with unit.	
b. Test 2: Gradual increase in activity.	
c. Test 3: Evaluate apparatus under different work and physical orientation.	
d. Test 4: Provide information on operating and breathing characteristics of the unit under actual use.	
e. Test 5: Determine maximum length of time unit will last at rest.	
f. Performance test per 30 CFR 11.85-18.	
g. Gas tightness test per 30 CFR 11.85-19.	

F. Approval

1. After unit passes machine and man tests and documentation passes quality control, a NIOSH approval will be issued.

Action Item List For NIOSH Approval

1. Manufacturer. Generate Quality Control Plan per CFR Title 30 Chapter 1, Subpart E.
2. Manufacturer. Quality Control Plan submittal to NIOSH
3. NIOSH. Review and Approval of Quality Control Plan.
4. Manufacturer. Implementation of Quality Control Plan.

NOTE: Steps 1-4 may not be necessary if the breathing system manufacturer already has implemented a NIOSH approved Quality Control Plan.

5. Manufacturer. Make Class A drawings of all parts and subassemblies.
6. Manufacturer. Fabricate all production tooling required to manufacture a production unit.
7. Manufacturer. Manufacture production breathing system(s). (As many as requested by NIOSH)
8. Manufacturer. Pre-Testing of production unit with all tests to be conducted by NIOSH. Prepare all documentation of pre-testing.
9. Manufacturer. Generate application per 30 CFR part 11-11 (to include all documentation and pre-test data as previously defined).
10. Manufacturer. Submittal of application and production unit(s) to NIOSH. Also fees per 30 CFR part 11.20
11. NIOSH. Conduct all Bench and Man tests as previously defined.
12. NIOSH. Issue approval.

V. REFERENCES

U.S. Divers Co., Phase I Design Report for the 2.5 Hour Rebreather, December 14, 1979.

U.S. Divers Co., Operating and Maintenance Instructions for the 2.5 Hour Prototype Rebreather/Pressurization System, January 1981.

U.S. Divers Co., Safety Assessment Report for the 2.5 Hour, Closed Circuit Life Support System, January 1981.



FIGURE 1: "Bag Permeability Test"



FIGURE 2: "Suit Make-up Regulator Test"



FIGURE 3: "Connecting the Suit Make-up Regulator"

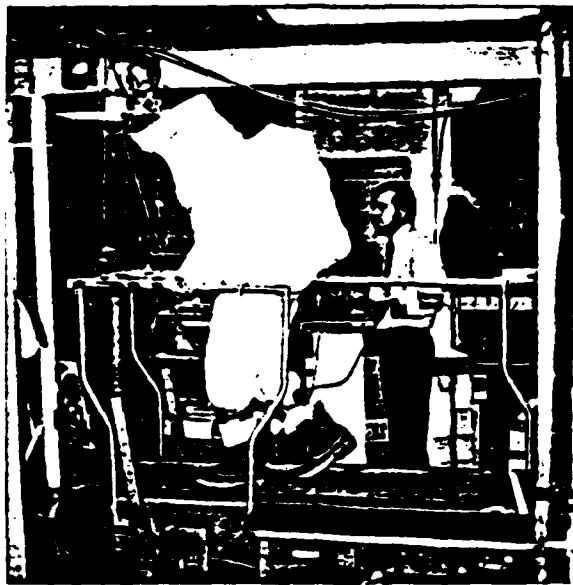


FIGURE 4: "Man Test with HCPCO"
(Man Test No. 6)

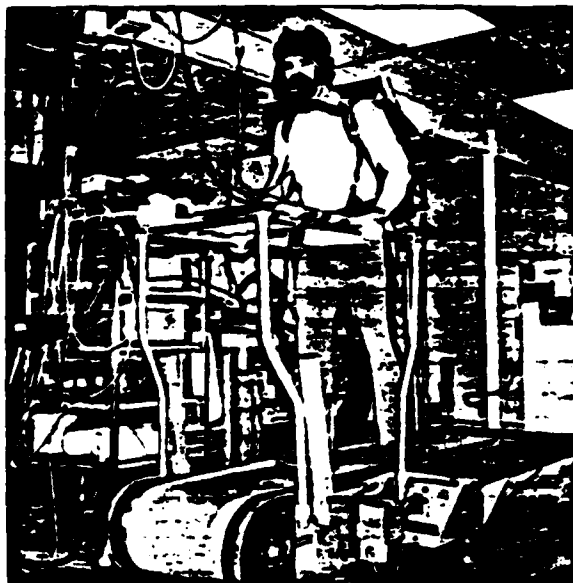
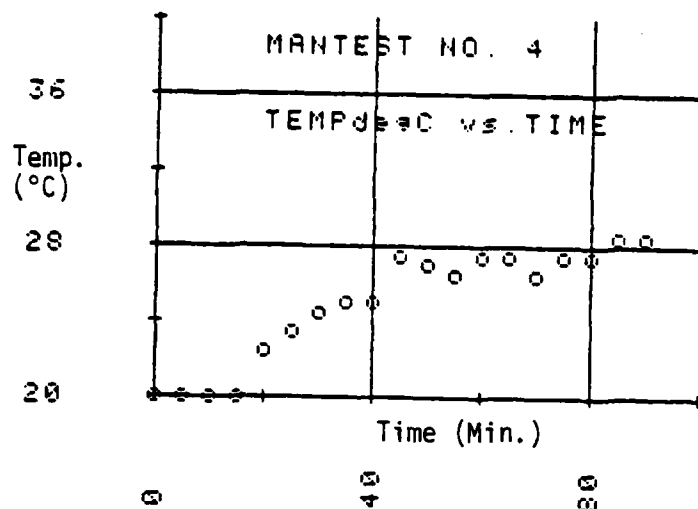


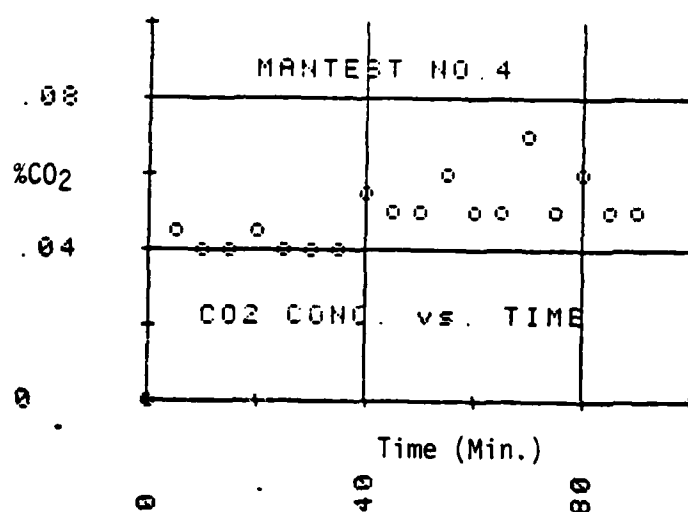
FIGURE 5: "Man Test No. 3"
Man Test 12/23/80



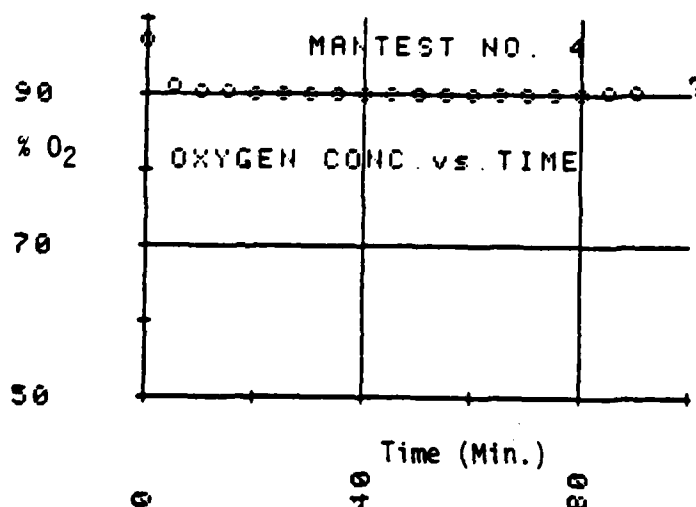
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Test Duration

90 Min.

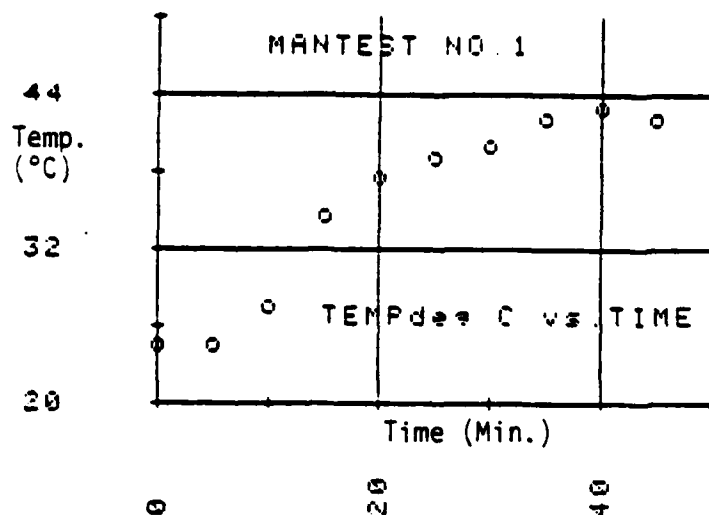


NOTE: CO₂ concentration is measured in the facemask.



NOTE: O₂ concentration is measured in the facemask.

FIGURE 6: Man Test No. 4



DATA

Avg. Treadmill Speed 3.33 mph

Constant CO₂ Concentration 0%

Avg. V_O₂ 2.14 lpm

Test Duration 45 Min.

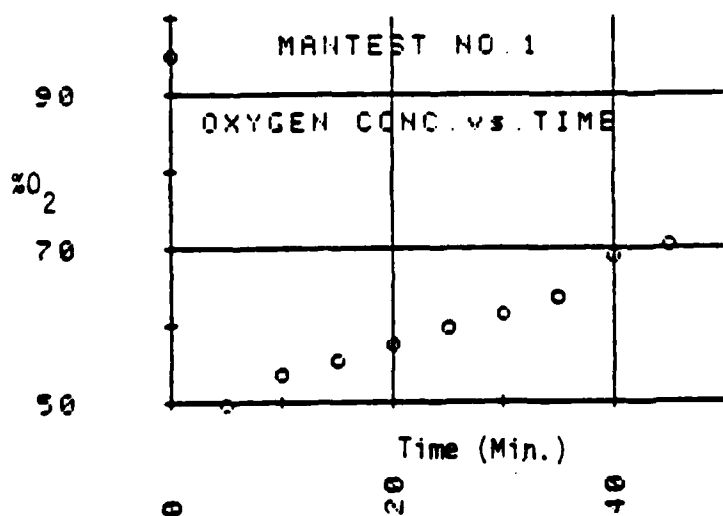
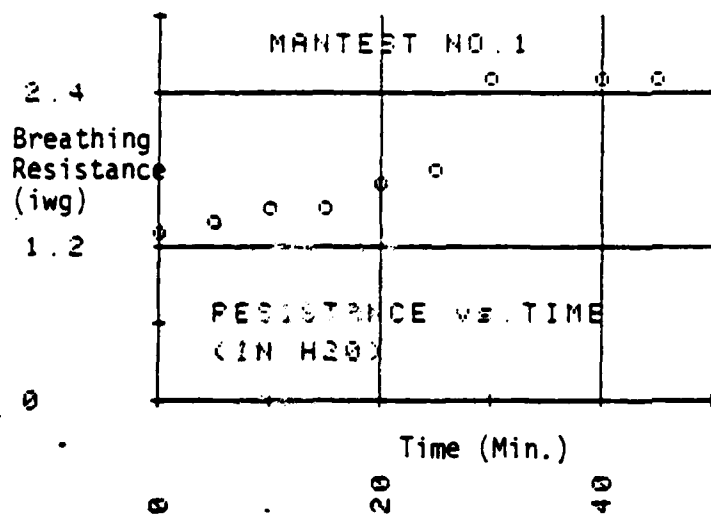
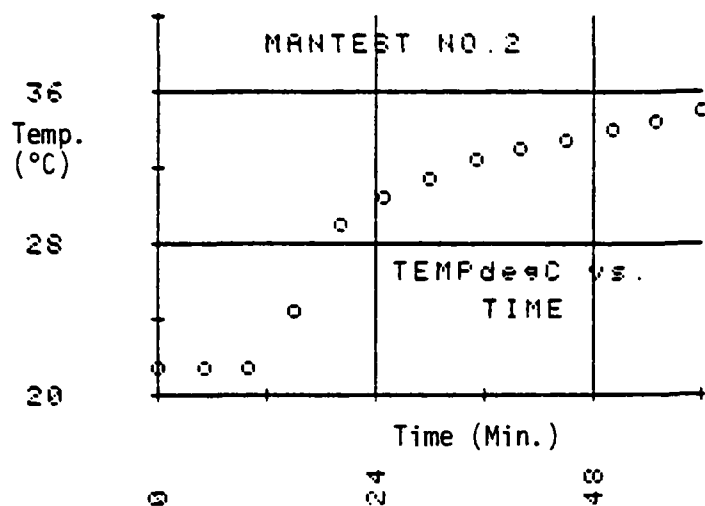


FIGURE 7: Man Test No. 1



DATA

Avg. Treadmill Speed	2.75 mph
Avg. $\dot{V}O_2$	1.5 lpm
Avg. \dot{V}_E	25 breaths/min.
Test Duration	60 Min.

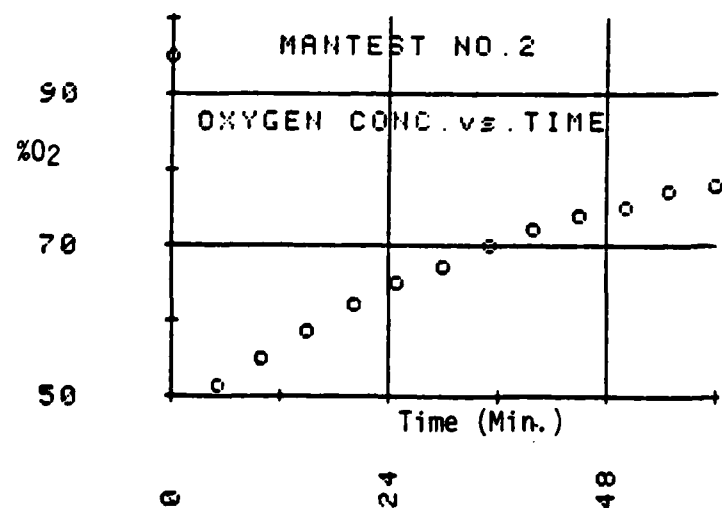
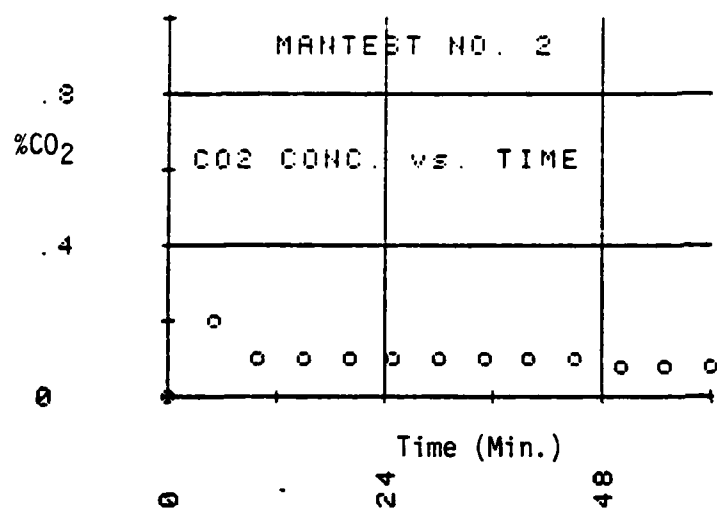
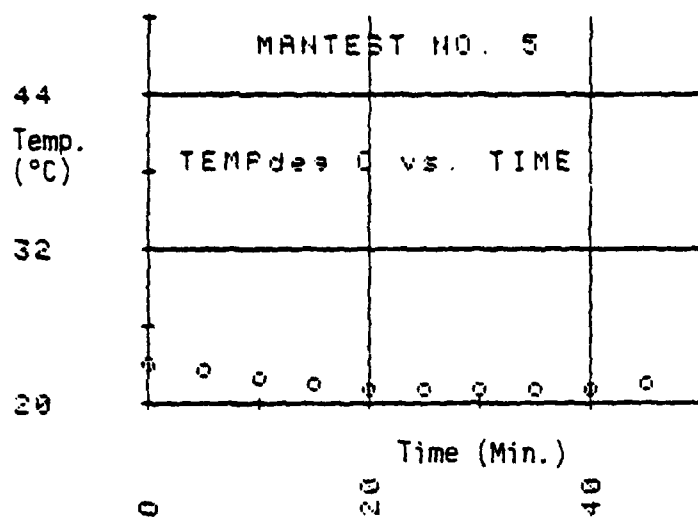


FIGURE 8: Man Test No. 2



DATA

Avg. V_E	25 lpm
CO ₂ Concentration Constant	0%
Treadmill Speed	1.5 mph
Test Duration	45 Min.

Test No. 5 was performed in HCPCO.

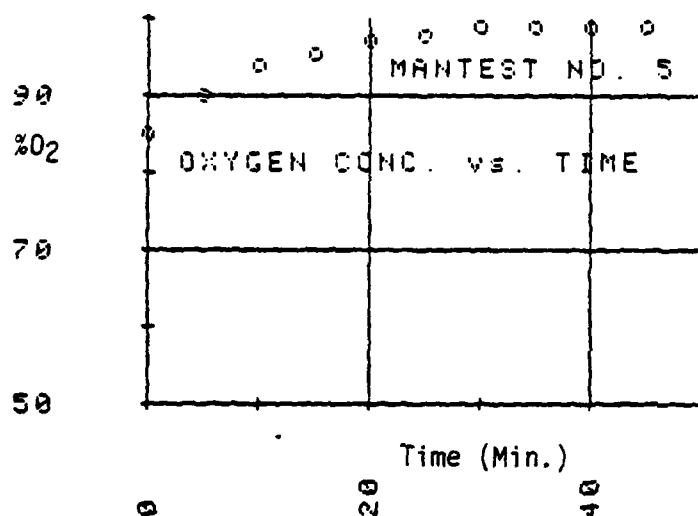
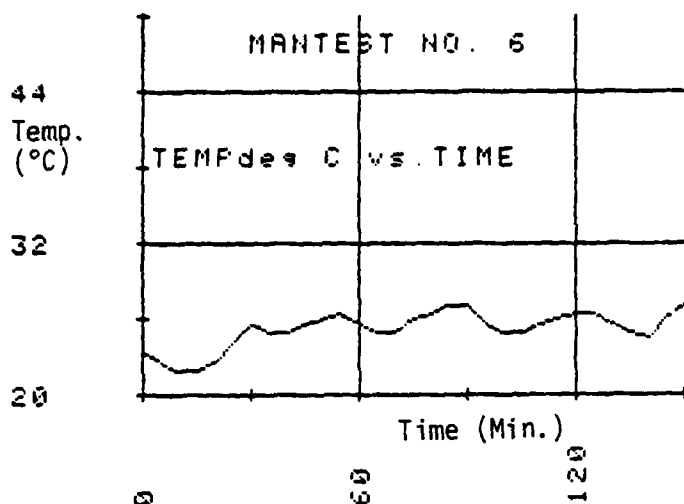


FIGURE 9: Man Test No. 5



DATA

Avg. Treadmill Speed	1.5 mph
Avg. $\dot{V}O_2$	2.26 lpm
Constant CO_2 Concentration	0%
Test Duration	150 Min.

Test No. 6 was performed in HCPCO.

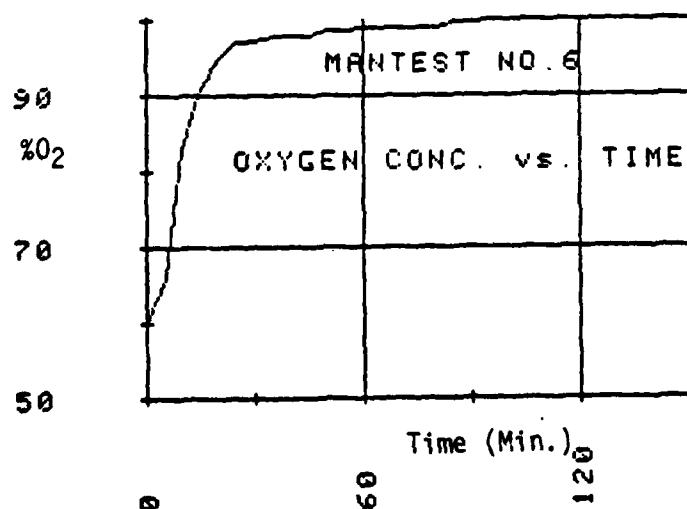
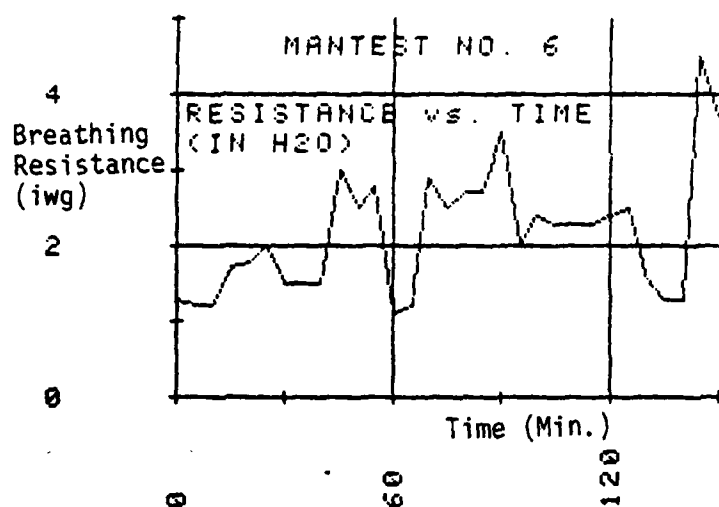


FIGURE 10: Man Test No. 6

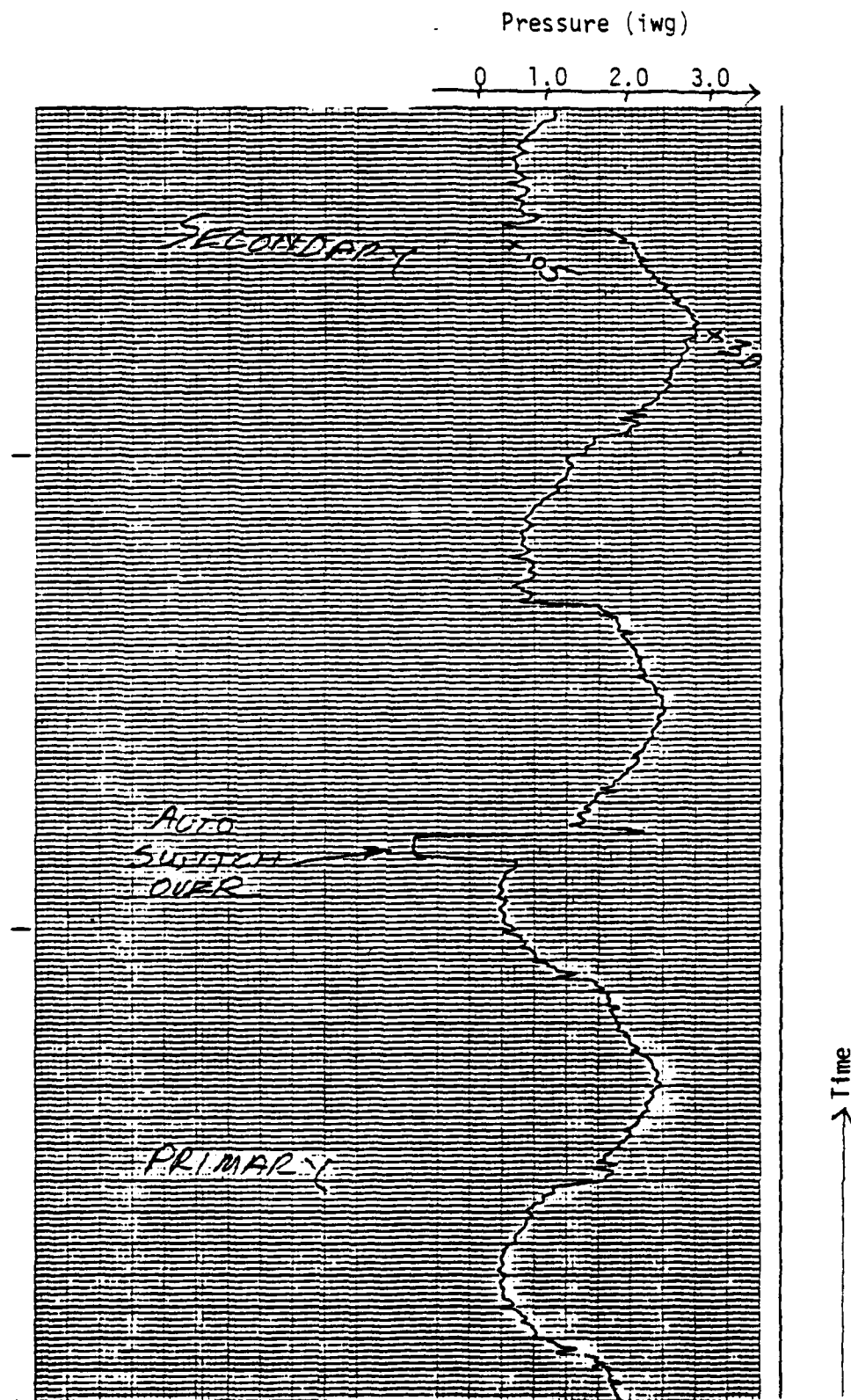


FIGURE 11: Automatic Switchover

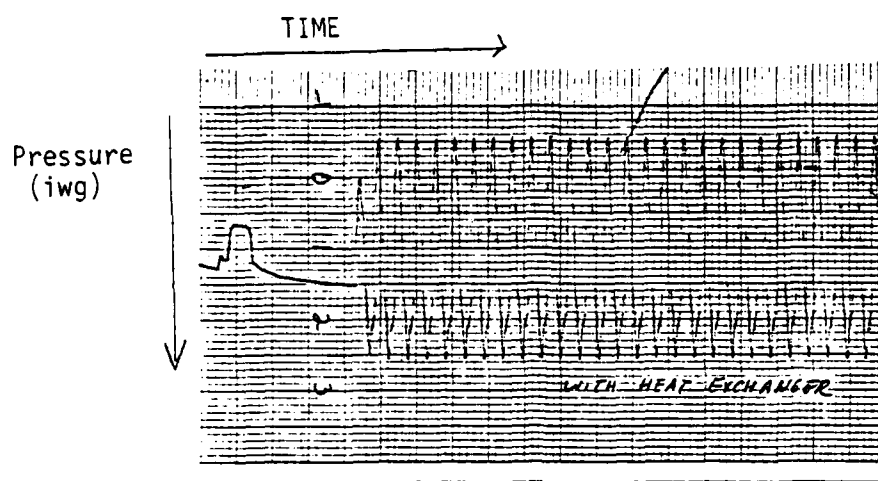


FIGURE 12: Original Resistance (peak to peak)

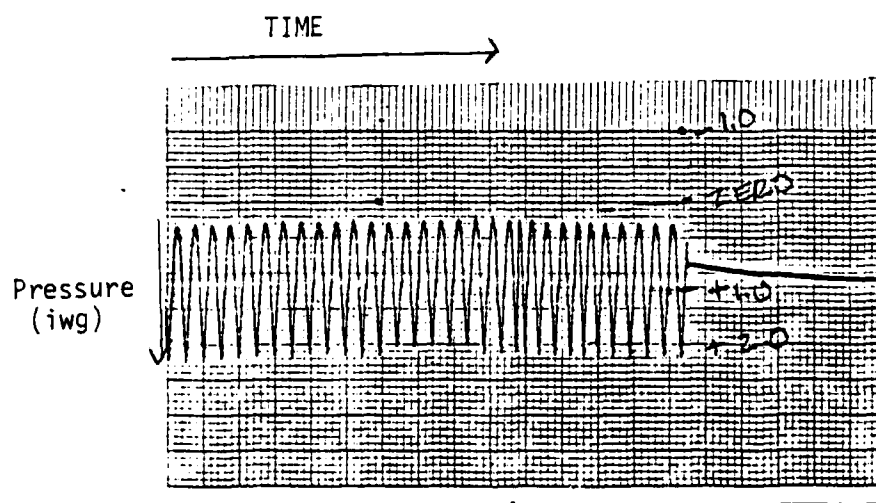


FIGURE 13: Resistance After Redesign

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